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Confinement Studies in High Temperature Spheromak Plasmas*

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Abstract. Recent results from the SSPX spheromak experiment demonstrate the potential for obtaining good energy confinement (Te > 350eV and radial electron thermal diffusivity comparable to tokamak L-mode values) in a completely self-organized toroidal plasma. A strong decrease in thermal conductivity with temperature is observed and at the highest temperatures, transport is well below that expected from the Rechester-Rosenbluth model. Addition of a new capacitor bank has produced 60% higher magnetic fields and almost tripled the pulse length to 11ms. For plasmas with T_e > 300eV, it becomes feasible to use modest (1.8MW) neutral beam injection (NBI) heating to significantly change the power balance in the core plasma, making it an effective tool for improving transport analysis. We are now developing detailed designs for adding NBI to SSPX and have developed a new module for the CORSICA transport code to compute the correct fast-ion orbits in SSPX so that we can simulate the effect of adding NBI; initial results predict that such heating can raise the electron temperature and total plasma pressure in the core by a factor of two.

1. Introduction

Recent operation of the SSPX experiment produced spheromak plasmas with good energy confinement (T_e > 350eV and radial electron thermal diffusivity $\chi_e < 10m^2/s$) for short periods (~2ms) [1]. This is a remarkable demonstration of plasma self-organization and relaxation into a symmetric toroidal configuration. These results motivate adding neutral beam heating to provide a controlled heat source for transport and beta-limit studies and to further increase the plasma temperature. Until now, spheromak plasmas were heated solely by resistive dissipation of internal plasma current (ohmic heating). In the near term, while procuring the neutral beam, we are using a new programmable modular capacitor bank to produce higher magnetic fields and longer pulses, and to study the physics of magnetic field generation in the spheromak. Efficient magnetic field generation is key to developing the spheromak as a potential magnetic confinement fusion energy concept.

Spheromak plasmas in SSPX are produced using DC coaxial helicity injection [2,3]. Coaxial gun currents range from 200 to 650kA with total vacuum flux of 12-60mWb. The resulting spheromak plasma is confined inside a 2cm thick tungsten-coated copper flux conserver, which provides passive stability to tilt and shift modes. Pulse lengths range from 1-10 msec, with confined toroidal plasma currents ranging from 400 to 700kA, resulting in edge poloidal fields ranging from 0.2 to 0.5T with corresponding toroidal field on the magnetic axis of 0.4 to 0.9T. Plasma major radius is 0.31m and minor radius is 0.18 m, with a central current column radius of ~0.12m for most discharges.

High performance discharges result from taking advantage of the fundamental operational flexibility of SSPX and from paying close attention to wall conditioning to minimize impurity content [4]. Power to the coaxial gun is provided by three independent capacitor banks: 1) a 0.5MJ formation bank provides 3-10kV pulses with fast rise time (70μs to 90% peak current) for initial breakdown and ejection from the gun; 2) a 1.5MJ sustainment bank and associated

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inductor act as a pulse-forming network to deliver 2-5kV flat-top current pulses to drive edge current during sustainment ; and 3) a new programmable 1.5 MJ solid-state modular capacitor bank to increase peak current and extend the pulse duration. The combination of these three banks provides a wide range of possible current waveforms, which can be used to maximize the confining fields and optimize the internal current profile so as to minimize magnetic fluctuations.

In addition to the ability to control the internal current profile by adjusting the gun current waveform, we can vary the bias magnetic field configuration using a set of nine independently controllable external field coils. We can vary the spheromak formation threshold current by adjusting the fraction of vacuum flux passing through the flux conserver as compared to that remaining in the coaxial source region. The Standard configuration keeps more than 90% of the flux in the coaxial region, whereas the most commonly run configuration, Modified Flux, has 40% of the flux linking the flux conserver. The BCS configuration pulls more than 80% of the vacuum flux down the central axis of flux conserver. While the modified flux configurations produces the cleanest and hottest plasmas, all configurations yield about the same spheromak edge poloidal field for a given gun current.

Limiting impurity radiation is important to achieving high performance. In SSPX, we rely on high temperature baking (100 hours at 165C), titantium gettering of the flux conserver every 4-5 discharges, and helium shot conditioning. These techniques help control plasma density and impurity content. Recently we discovered that the 100μm thick tungsten coating on the inner electrode (the cathode) of SSPX has failed and sections of it, at one end of the ~25cm dia. central current column, now show exposed copper. While spectroscopy does not show clear evidence for copper contamination, it has become increasingly difficult to produce high temperature plasmas, so we are recoating with tungsten.

2. Energy Transport in High Temperature Plasmas

High-temperature discharges in SSPX are obtained by flattening the safety-factor (q) profile to eliminate low-order resonant magnetic surfaces and thereby minimize magnetic fluctuations [5]. This is achieved by operating the coaxial injector at currents such that $\lambda_g=\mu_0 I_g/\psi_g$ is slightly less than the eigenvalue of the flux conserver, λ_{fc} , given by solution of $\nabla\times\mathbf{B}=\lambda_{fc}\mathbf{B}$ for the SSPX geometry (here $\lambda=\mu_0 j/B$ with ψ_g = applied poloidal magnetic flux and I_g is the gun current). Since ejection and formation require a higher initial current pulse ($\psi_{eject} \sim 2\lambda_{fc}$), the practical result of keeping $\lambda_g < \lambda_{fc}$ is that the spheromak magnetic field slowly decays on a resistive timescale, τ_r(core) > 10msec). Ohmic heating during this slow decay raises the plasma temperature from less than 50ev to values as high as 350eV. Overall global stability of the discharge is maintained as the plasma heats by providing sufficient edge current density on the open field lines surrounding the spheromak. Without this sustaining current, the plasma becomes unstable due to contraction of the current profile by resistive dissipation in the colder edge regions (T_{edge} ~30-50eV).

The most recent improvement in performance, raising T_e from 200eV to >350eV, was obtained by raising the magnetic field about 17%, which required a 4% increase in peak formation current and a 20% increase in injector magnetic flux and peak formation current, yielding B_{tor} > 0.7T on axis. SSPX data at constant density (~ $5\text{-}7\times10^{19}/m^3$), as in Fig. 1, show strong scaling of electron temperature with magnetic field. While the trend in the data suggest that SSPX is operating at an electron beta limit ($\beta_e \sim 5\%$), it can also be explained by postulating that the perpendicular thermal diffusivity, χ_e, scales with the resistivity in these ohmically heated discharges. Adding auxiliary heating to provide a controlled heat source would help remove this ambiguity.

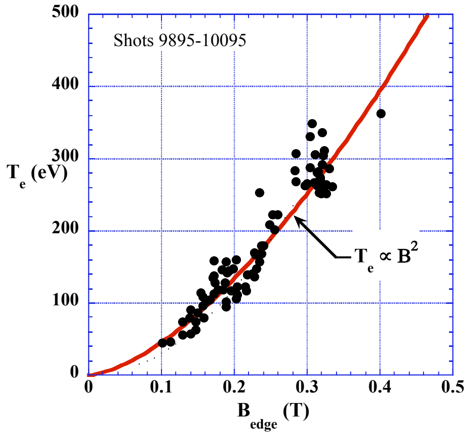

Fig 1. Peak electron temperature vs. edge polodal field. $B_{tor}(axis)=1.85B_{pol}(edge)$.

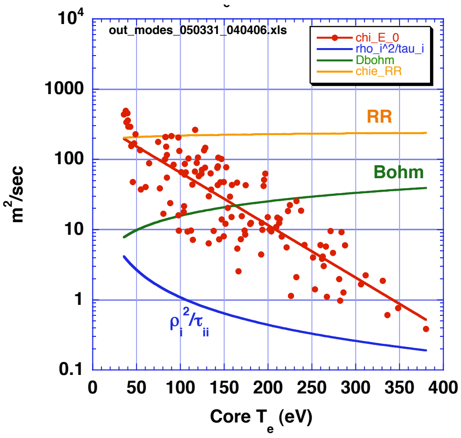

Fig 2. χ_e vs. Te for SSPX compared to Rechester-Rosenbluth (RR), Bohm, and collisional transport.

Electron temperatures in SSPX are consistent with the existence of good flux surfaces, and far exceed those expected for open field-line transport. The core electron thermal diffusivity, inferred from ohmic power balance, drops rapidly as T_e rises, as shown in Fig. 2. At the highest temperatures, χ_e is well below $10m^2/s$, which is in the range of tokamak L-mode discharges. Our transport analysis assumes $T_i=T_e$, sets $Z_{eff}=2.5$ based on spectroscopy, and uses MHD reconstruction to compute local current density. Recently we installed a neutral particle analyzer to measure the energy of neutrals escaping the plasma at the midplane; data show $E_0 < 150$eV for discharges with $T_e \leq 200$eV, though early in discharge, when magnetic fluctuations are higher, a 300eV tail appears in the neutral spectrum.

We have compared the observed χ_e scaling against several transport models, as shown by the solid lines in Fig. 2. In the case of Rechester-Rosenbluth stochastic field-line transport, we have assumed that the turbulent correlation length is the shorter of the collision length or one toroidal transit, and that the internal magnetic fluctuations can be characterized by edge measurements. At the highest temperatures, we suspect that a number of our assumptions, such as $T_i=T_e$, purely ohmic heating, and steady-state conditions, begin to break down, providing further motivation for the addition of controlled auxiliary heating to the experiment.

3. Increasing Pulse Duration and Magnetic Field

We have used the new modular capacitor bank (MB) to study magnetic field generation with the aim of increasing the field and pulse length to achieve higher T_e at constant β_e. The 30 MB modules contain a 5kV capacitor, an optically triggered thyristor switch, and a current-limiting inductor, and are tied directly to the injector via new low-impedance coax cables. Each module can deliver a 5kV, 50kJ 50kA current pulse, and by adjusting the relative timing of these pulses, we can generate a variety of current waveforms to drive the spheromak. The elimination of the pulse-forming network, along with the new cabling, significantly increases the fraction of bank energy coupled to the spheromak. When all three banks operate together, a total of 3.5MJ is available to drive SSPX discharges.

The modular bank was used in three operating modes: long-pulse sustainment, high-current formation, and multi-pulse buildup. These operating modes are illustrated below. In long-pulse sustainment, Fig. 3, the modules fire individually at fixed intervals of ~230μs, starting at the end of the sustainment bank pulse. In this way, the gun current can be maintained nearly constant with very little ripple ($\delta V/V$ ~1.2%). In these initial experiments the plasma resistivity was high, as evidenced by the relatively rapid drop in edge poloidal field following the formation pulse (comparing 14457 and 16531 in Fig. 3). We attribute this to damage to the tungsten coating covering the copper structure of the coaxial injector.

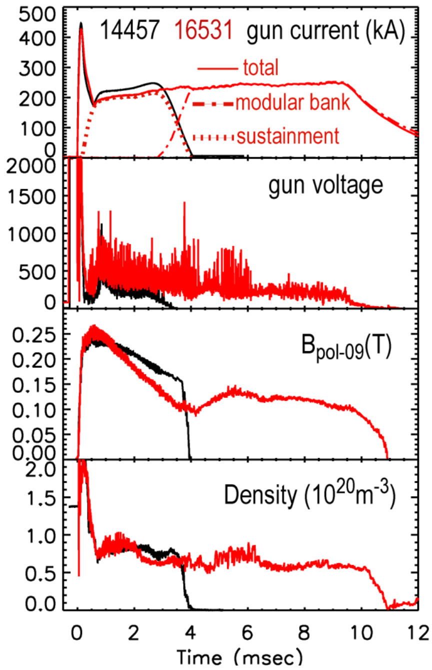

Fig. 3. Long pulse discharge with modular bank (16531) compared to standard discharge with

During the long pulse sustainment phase of 16531, the edge poloidal field actually begins to increase again starting at 4msec, when λ_g rises above $10m^{-1} \geq \lambda_{fc} = 9.9m^{-1}$. When the edge λ is higher than the spheromak λ, helicity moves from the gun to the core and the spheromak field and current start building. The mechanism for this helicity transport is still under consideration. NIMROD simulations associate the large spikes in gun voltage with short scale-length reconnection events near the X-point at the mouth of the coaxial injector [6]. After t=6ms, the field begins decaying again even though λ_g remains greater than λ_{fc} and the edge magnetic fluctuations, dB_{pol}/B_{pol}, remain 2-3 times higher than in our hottest plasmas, which are slowly decaying. We are unsure why this is so. In the near term, after we recoat the injector, we will adjust the drive current to maintain the field while minimizing fluctuations.

We have also used the modular bank to increase the spheromak magnetic field by producing high current formation pulses. Increasing the gun current was motivated by our experience on SSPX that there is a stiff upper bound on the maximum spheromak edge poloidal field for a given gun current [7,8]: $B_{pol} \leq 0.65 I_g$. By compressing the time over which we fire the 30 MB modules, we get higher currents, which we can sustain for longer duration due to the greater stored energy and lower loss of the MB system, as shown in Fig. 4. The factor of two increase in peak edge poloidal field results from higher current (×1.3) and improved current utilization (×1.5, B_{pol}/I_{gun}=0.85 for 16537 vs. 0.55 for 12590). For discharge 16111, the peak current is only 10% higher than 12590, but the peak field is 1.6 times larger, again pointing to a 50% increase in current utilization. We believe this is related to the duration of formation pulse compared to the helicity decay time (see below). Peak toroidal field at the magnetic axis, as determined from CORSICA MHD reconstruction, reaches 0.9T for this discharge.

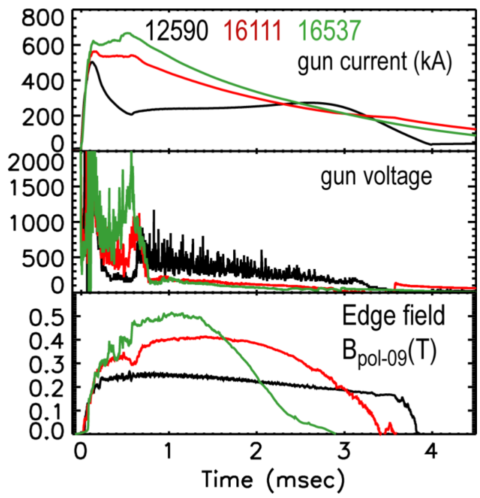

Fig. 4. High current formation discharges (16111, 16537) compared to standard operation (12590).

Prior to operating the new modular bank, we used the NIMROD 3D resistive MHD code [9] to predict how it would impact SSPX performance. Detailed comparisons of NIMROD results with SSPX data show that NIMROD reproduces many features of present discharges, including the edge magnetic field, the spectrum and amplitude of low-order MHD modes [10], and the relative magnitude and frequency of spikes in the gun voltage which are associated with reconnection events [6]. For simulating operation with the modular bank, NIMROD was modified to use the external circuit parameters of the SSPX capacitor bank to control the gun voltage and current vs. time. With peak injected gun currents ~800kA, NIMROD predicts peak edge fields more than twice present values (B_{pol}(edge) ~0.8 T vs. ~0.3 T with peak currents ~400A) and substantially higher electron temperatures. Figure 5 shows NIMROD results for the voltage and poloidal magnetic field at the edge of the flux conserver midplane as functions of time for a given programmed gun current trace. In this case, the simulation yields B_{pol}/I_{gun}=1.0, as compared to 0.85 for SSPX pulse 16537, which is very good agreement considering that the code starts from scratch with only the flux conserver, vacuum magnetic flux, applied gun voltage, and a uniform plasma density to simulate initial breakdown.

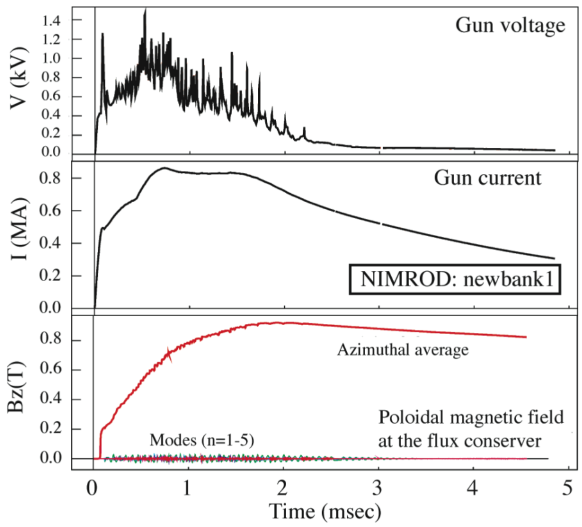

Fig. 5. NIMROD simulation of high-current formation pulse as with SSPX modular bank.

Multi-pulse buildup represents the third way in which we have used the new modular bank to study magnetic field generation. Previous experiments in SSPX showed that helicity could be added to the spheromak in discrete steps by repetitively pulsing the coaxial source [8]. While only two pulses could be applied due to limitations in the capacitor bank, the magnetic field energy (and helicity) content of the plasma increased with each pulse. The final field achieved a current utilization significantly higher than had been observed with only a single pulse: B/I=0.85.

We have used the modular bank to produce five distinct current pulses, as in Figure 6. The poloidal field and total field energy (W_b) builds with each pulse, though with steadily decreasing energy efficiency for each pulse ($\delta W_b/\delta\int I_g V_g dt$ = 0.1, 0.15, 0.08, 0.05, and 0.04), presumably because more of the gun power is used to maintain the field. The final field obtained, 0.25T, corresponds to B/I=0.77, a little lower than that of the high-current discharge 16537, which may be due to not operating at optimal λ_g. We do not yet understand why the second pulse obtains so much larger energy efficiency than the other pulses. It is important to note that, in contrast to many earlier double-pulse experiments, the plasma density remains nearly constant with each additional pulse.

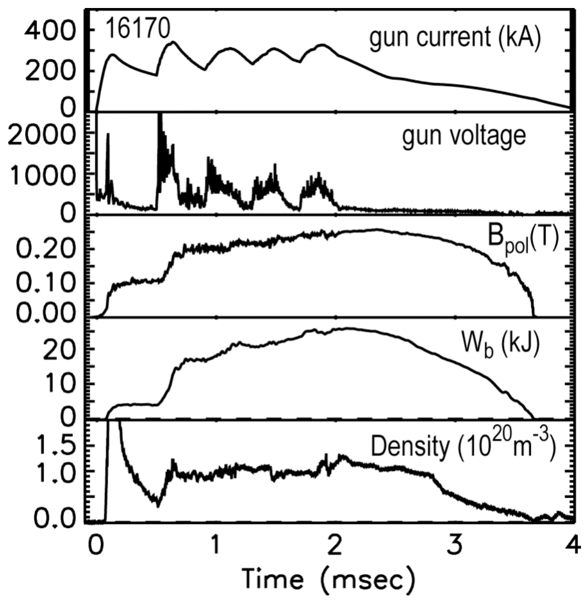

Fig. 6. Multipulse buildup discharge using five distinct current pulses from the modular bank.

4. Simulation of Neutral Beam Heating

Achieving high plasma temperatures, 1.0T internal magnetic fields, and producing 10msec discharges in SSPX provides strong motivation for the addition of neutral beam injection (NBI) auxiliary heating. Addition of NBI decouples the heating from the plasma current (and confining field) and provides capability for directly measuring heat loss from the core. With $T_e > 300$eV, a modest 1.8MW NBI heat pulse can significantly change the power balance in the core plasma raising both plasma temperature and pressure. Consequently, we are now planning to procure two 0.9MW, 25keV 5ms neutral beams from the Budker Institute in Russia to install on SSPX. The beams have a small enough waist to enter the SSPX flux conserver through an existing 5cm tall diagnostic slot.

Before moving forward with the beam procurement, we used the CORSICA 2D Grad-Shafranov code to simulate SSPX neutral beam heating scenarios to better quantify expected results. CORSICA computes heat and particle transport, as well as self-consistent changes in the MHD equilibrium using a variety of transport models. Because the ratio of B_{pol}/B_{tor} is very different for a spheromak compared to high-aspect-ratio tokamaks, and because the fields are low, we had to develop a new module for CORSICA to construct the correct fast ion orbits in SSPX geometry [11]. This module, coupled to a deposition code (NFREYA), is used to calculate the particle, current and power deposition from neutral beam injection. While exact orbit-following codes are potentially more accurate and have been developed for use on spheromak equilibrium [12], the CORSICA code is fast and robust and is linked to the everyday equilibrium reconstruction of SSPX discharges. The fast-ion module was benchmarked against other simulations of the low-aspect ratio NSTX spherical torus.

CORSICA simulations of neutral beam heating use parameters typical of high temperature discharges in SSPX. As a starting point for this work, we used the equilibrium and plasma cross section generated from shot 12367, which was driven by 500kA formation pulse, 240kA sustainment pulse, with 34mWb bias magnetic flux. The resulting spheromak had 325kA toroidal current, B_{Tor}=0.45 on the magnetic axis, and edge B_{pol}= 0.25T at the outboard midplane (#12367). Peak electron temperature and line-average density was 250eV and 7×10^{19}m^{-3}, respectively. Fig 7 shows the computed hydrogen neutral beam deposition profile as compared to the flux conserver and plasma cross sections (the beam enters radially through the diagnostic slot on the right). There is good penetration of the beam without significant shinethrough, so most fast ions are born relatively close the magnetic axis. The ion gyroradius is 4cm near the magnetic axis.

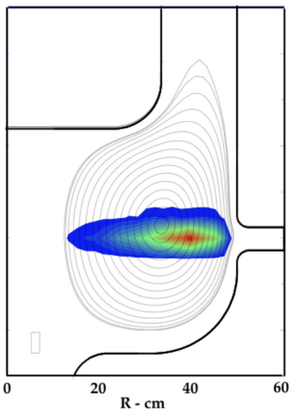

Fig. 7. Computed beam deposition overlaid on flux surfaces. Magnetic axis at R=31cm.

CORSICA results show that a substantial fraction of the injected 25keV beam, of order 70%, would be confined as fast ions in a typical SSPX discharge. Three classes of particle orbits are observed: passing, trapped, and potato orbits (particles which are passing but do not encircle the magnetic axis. Fig. 8 shows three such representative orbits. Before we completed the simulation, there was considerable concern that fast-ion orbits in the spheromak would not be well confined and neutral beam heating would be inefficient, but this does not appear to be the case for these plasmas when the ions are born at least one ion gyroradius inside the separatrix. Operation at the higher currents and fields obtainable with the modular bank will improve the situation.

Given the expectation of adequate fast-ion confinement, we used CORSICA to compute the response of the plasma to the NBI heating. For this purpose, we froze the magnetic equilibrium and density profile and solved for the evolution of the temperature profiles only, since good models for particle transport and the dynamo electric field in a sustained spheromak are lacking. In addition to T_i and T_e profiles, CORSICA computes relevant beam-related quantities such as the prompt fast ion losses, fast-ion density and pressure and local β and the resulting neutral beam driven current density. Initial Te and ne profiles were obtained from SSPX Thomson scattering measurements, and the thermal diffusivities were inferred from ohmic power balance. In this analysis we set $\chi_i = \chi_e = 10\mathrm{m}^2/\mathrm{s}$ on the magnetic axis, so T_i, which we do not measure, starts off a factor of two lower than T_e in the simulations.

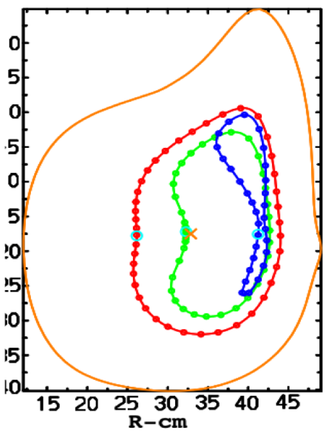

Fig. 8. Guiding center motion for ***passing***, ***trapped***, *and* ***potato*** *orbits. x marks the magnetic axis.*

Our modeling predicts a significant temperature increase resulting from application of 1.5MW of neutral beam heating. The total beam heating power (to ions + electrons) exceeds the ohmic heating power across the inner half of the minor radius. Peak electron temperature rises from 220eV to 300eV and T_i increases from 110eV to 170eV over a period of 4 ms, after which steady state conditions obtain (set by fast ion slowdown or other loss rates). By the end of the 4ms heating pulse, fast ions are responsible for half of the 100% increase in plasma pressure, as shown by the pressure profiles plotted in Fig. 9. The predicted temperature rise is sensitive to choice of transport coefficients, though as the plasma gets hotter it takes longer for the beam ions to heat the bulk due to reduced collisionality.

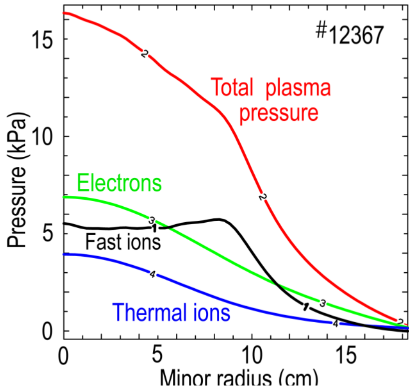

Fig. 9. Computed pressure profiles at end of 4ms NBI heat pulse.

The CORSICA modeling has also provided useful information for NBI system design. While the beam parameters are pretty much fixed, the injection geometry can be varied to optimize results. Originally, we focused on radial injection to maximize the beam penetration so that fast ions would be born as close to the magnetic axis as possible, since we were concerned about orbit quality. Using the same plasma parameters and transport coefficients as above, we varied the injection angle to span fully co- to fully counter-current injection. A significant variation in heating was observed (see Fig. 10): the maximum T_e rose from 300eV to nearly 400eV for co-injection tangential to the magnetic axis and was only slightly less (375eV) for counter current injection. With co-injection, neutral beam current drive amounted to 13% of the total plasma toroidal current. More interesting, near the axis the beams doubled the current density, opening up the possibility that NBI could significantly change the current profile and MHD stability of the spheromak. Active control of the internal current profile might prove very useful for study of dynamo physics in the spheromak.

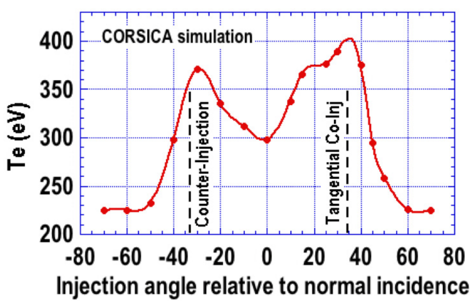

Fig. 10. Variation of computed peak Te vs. NBI injection angle for SSPX.

5. Discussion

New, more flexible power systems, careful attention to wall conditioning, and improved understanding of the relationship between the gun parameters, the internal current profile, and magnetic reconnection are all contributing to producing dramatic improvements in the performance of driven spheromak plasmas. Numerical simulation with the NIMROD code, validated against experiment, now provides a framework for understanding how controlling the current profile by adjusting the edge λ with the sustainment bank can be used to avoid unstable modes. Though small amplitude, these unstable modes significantly damage the quality of the flux surfaces and spoil confinement. Reconstruction of the current profile using CORSICA is a key part of this process.

Efficient magnetic field generation remains a challenge for the spheromak concept, since higher fields are needed to allow heating to higher temperature. The stiff proportionality between peak field and peak injector current, regardless of the initial flux configuration or buildup method, suggests that a fundamental process governs the field generation based upon DC coaxial helicity injection. NIMROD simulations are tantalizing in reproducing the SSPX flux amplification, but a clear physical understanding of the limiting processes still eludes us and presents a clear challenge to increasing the field.

Given the higher plasma temperatures obtained on SSPX (T_e > 300eV) neutral beams now look to be a promising tool for improving understanding of energy confinement, transport processes, and pressure limits in the spheromak. In addition to simply increasing the plasma temperature, neutral beam heating would also make possible new internal measurements, such as Ti, ñ, j(r). Experience shows that adding NBI heating always produces significant qualitative and quantitative improvements to the scientific output of magnetic fusion experiments.

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